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MODELING THE EVOLUTION OF STRENGTH DURING WIRE DRAWING

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Abstract

Extensive plastic deformation during wire drawing is commonly used to produce steel wires with very high strengths. Typically these steels are eutectoid and hypereutectoid steels and drawing strains up to 4 are used during processing. The resulting materials can have tensile strengths in excess of 4000 MPa. The evolution of microstructure and the strengthening mechanisms resulting from wire drawing have been studied for eutectoid and hypereutectoid steels. Strength has been shown to be a function of pearlite colony size, interlamellar spacing and the size of the stable dislocation cells that are produced during wire drawing. The results have been used to model the evolution of strength during wire drawing. Model predictions for the evolution of tensile strength with drawing strain show excellent agreement with data derived from a number of eutectoid and hyperectectoid steels as a function of drawing strain.

Introduction

Wire drawing is commonly used to produce steel wires with high strengths. Typically these steels are eutectoid and hypereutectoid steels and drawing strains up to 4 are used during processing. Several investigators have studied the evolution of microstructure during drawing of mildly hypereutectoid steels [1-3] and iron [3,4]. The starting microstructure for wire drawing of eutectoid and hypereutectoid steels is fine pearlite with randomly oriented lamellae. The fine pearlite results from a patenting heat treatment. The mean free ferrite path in a eutectoid steel after patenting is typically 90 nm. Increasing the carbon content will decrease the mean free ferrite path. The resulting properties have also been previously described [5,6]. This paper is primarily concerned with strengthening mechanisms in severely drawn, pearlitic steel wire. These strengthening mechanisms are introduced into a model that describes the evolution of strength during wire drawing. The model predictions for the evolution of tensile strength strength with drawing strain are then compared with data derived from a number of eutectoid and hyperectectoid steels as a function of drawing strain.

Microstructural Evolution During Wire Drawing

The microstructural evolution of a eutectoid composition steel during wire drawing is shown schematically in Fig. 1. Drawing produces considerable alignment of the pearlite plates parallel to the drawing direction and reduction in the mean free ferrite path. The ferrite also develops a <110> wire texture typical for BCC metals. Throughout the wire drawing process, the carbide plates deform to strains comparable to the ferrite plates and the carbide plates are also observed to fracture but not as much as might be expected. Recent work has also shown that partial dissolution of the cementite phase can occur during severe plastic deformation of pearlitic steels [7]. Dense dislocation tangles form in the ferrite and, at small drawing strains (approximately .25), dislocation cell walls form. These cell walls contain fragmented carbide particles. Transmission electron microscopy studies reveal that very few dislocations are found within the cells and a high dislocation density is found in the cell walls. With continuing deformation, these cells become thinner and resist extensive dynamic recovery. Embury et al. [2] have shown that the width of the cells scales as the diameter of the wire. The result is the development of a fine, stable substructure with very fine cell dimensions normal to the wire axis (e.g. < 10 nm).

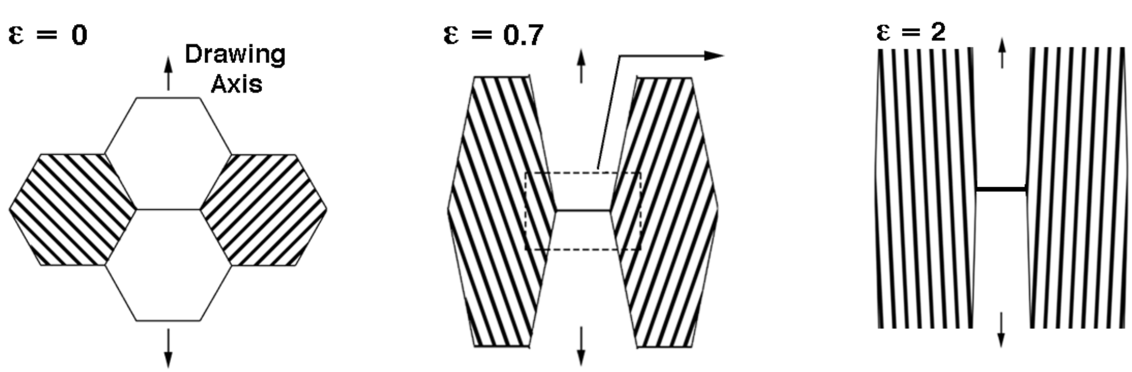

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Fig. 1. Schematic drawing showing the development of microstructure during drawing of eutectoid composition steel. Typical drawing strains are indicated in the figure.

Properties and Strengthening Mechanisms

The dominant deformation resistance in UHCS wire depends on the structure and substructure developed during processing. Previous studies of eutectoid and hypereutectoid steels [8, 9] with pearlitic microstructures have shown that, in the absence of severe plastic deformation, the yield strength is derived from hardening contributions associated with pearlite colony size, interlamellar carbide spacing and solute additions. The pearlite colony size and the interlamellar carbide spacing represent the dimensions of microstructural features that impose barriers to dislocation motion. These strengthening mechanisms contribute to the yield strength in an additive manner and, for eutectoid and hypereutectoid steel with pearlitic microstructure, the following equation has been derived.

$$\sigma_y = (\sigma_o)_{ss} + 145(D)^{-1/2} + 460L^{-1/2} \qquad (1)$$

where σ_y is the yield strength, $(\sigma_o)_{ss}$ is the resistance to dislocation motion resulting from solid solution atoms, $(D)^{-1/2}$ is the carbide spacing (interlamellar spacing) and L is the pearlite colony size.

After severe plastic deformation, additional strengthening mechanism(s) are introduced. A number of investigators have studied the increase in strength that results from cold drawing of eutectoid and hypereutectoid steel wires [1, 5, 10-13]. Most of these studies have reported strength as a function of wire diameter. Data from seven such materials are shown in Fig. 2. Five of these materials are hypereutectoid composition wires and two of the materials are eutectoid composition wire (piano wire and the data of Kim). The starting strength in all these studies is derived from a fully pearlitic microstructure produced as a result of a patenting treatment. The strengthening produced by patenting to obtain these microstructures represents an important starting point for the very high strengths typically observed in severely drawn wire. The influence of cold wire drawing on the strength of hypereutectoid steels can be understood through further analysis of the data in Fig. 2. The increase in strength resulting from cold wire drawing was calculated as a function of drawing strain by subtracting the strength in the patented condition from the strength of the wire in the cold-drawn condition. Results are shown in Fig. 3 for three hypereutectoid steels with similar compositions. These materials had different as-patented strengths and different starting diameters. The results fall on a common curve suggesting that a common mechanism is responsible for the increase in strength by wire drawing. It is also important to recognize that, even after a drawing strain of 4, the strength of the wire is continuing to increase with increasing strain. These high work hardening rates at high strains are in contrast to the work hardening rates in FCC metals [2], which are substantially lower. The reduced work hardening rates in FCC metals at large strains result from more extensive dynamic recovery and thus a slower rate of reduction in the size of dislocation substructures relative to iron.

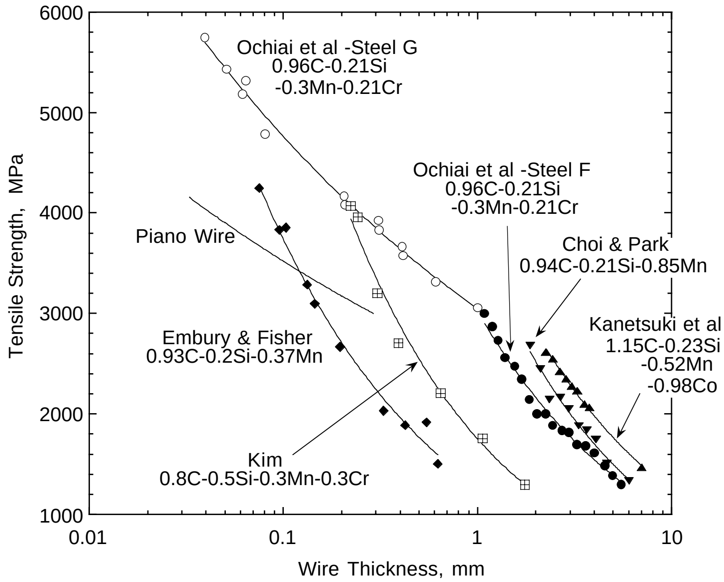

Fig. 2. Tensile strength as a function of wire diameter during wire drawing for eutectoid and hypereutectoid steels.

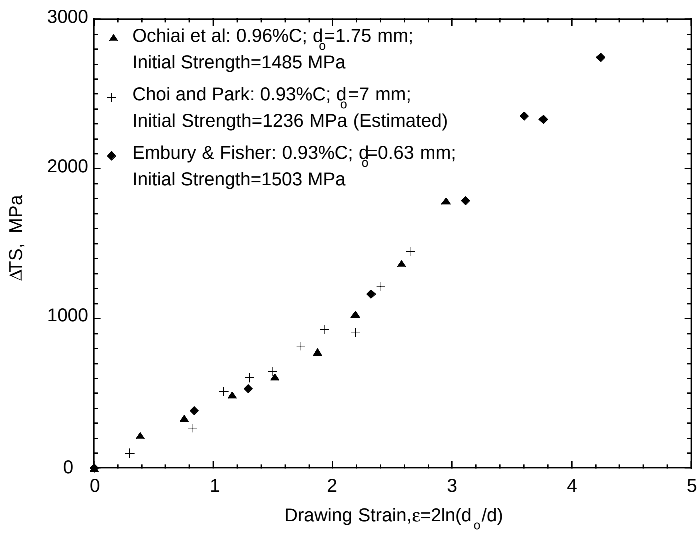

Fig. 3. Strength increment as a function of wire drawing strain in hypereutectoid steels with similar composition.

Embury and Fisher[1] have studied the principal strengthening mechanisms resulting from cold wire drawing in a Fe-.93C-.2Si-.37Mn wire. As discussed above, wire drawing develops a stable, cellular substructure consisting of narrow, oriented dislocation cells, which are the dominant source of strengthening in these materials. In Fig. 4, the variation of stress with cell size (measured normal to the drawing axis) is shown. The wire drawing produced very small cell sizes (10 nm and less). The yield strength of the wire was found to vary as the inverse square root of the width (λ) of the cells. Thus, in general terms,

$$\sigma_y = \sigma_o + k_y \lambda^{-n} \qquad (2)$$

where σ_y is the yield strength, σ_o is the strength from all sources other than dislocation cells, and k_y and n are constants. The strengthening in these severely drawn wires with stable substructures resulted from the cell walls acting as barriers to dislocation motion.

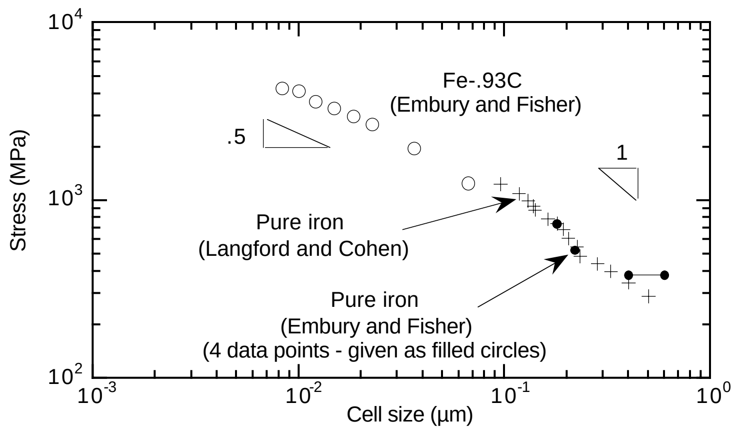

Fig. 4. Stress versus cell size for drawn Fe-.93C (data of Embury and Fisher[6]*) and pure iron. The pure iron data is from the two investigations (Embury and Fisher* [1] *and Langford and Cohen* [4]*).*

The contribution of a stable cellular structure to strengthening has also been studied by Langford and Cohen [4] for pure iron. In contrast to the work of Embury and Fisher, the yield strength was found to vary as an inverse linear function of the dislocation cell size (d^{-1}). The dependence of flow stress on d^{-1} was theorized to result from the work of deformation required to generate the length of dislocation line necessary to produce the imposed deformation. A comparison of the Embury and Fisher data on a Fe-.93C steel (which showed $d^{-1/2}$) and the Langford and Cohen data on pure iron (which showed that strength varied as d^{-1}) is shown in Fig. 4. Clearly different slopes are appropriate for the two data sets, although there is an overall continuity in the data for the two investigations. It is important to note, however, that, in addition to the Fe-.93C alloy, Embury and Fisher also studied a commercially pure iron (Ferrovac E) and concluded that the yield strength varied also as $d^{-1/2}$. Despite these differences, the results in Fig. 4 suggest a change in the dominant deformation resistance or significant contributions from other deformation mechanisms upon decreasing the cell size. Over the range of cell sizes studied, the strength varies as d^{-n} with n between .5 and 1. A more fundamental model for describing the relationship between strength and cell size will be presented in the next section.

Two observations relative to the strength levels shown in Fig. 4 are relevant to the various mechanisms of strengthening. First, the initial (as patented) strength before wire drawing is higher in the hypereutectoid steel than in pure iron. Clearly this difference arises from the strengthening effects of the carbide plates in the pearlitic steel. By analogy with the experimental work of Taleff et al. [8, 9], one might expect that the strength of a pearlitic steel results from the sum of strengthening contributions from different barriers to dislocation motion. Thus for a severely worked pearlitic steel,

$$\sigma_y = (\sigma_o)_{ss} + \sigma_{pearlite} + \sigma_{colony} + \sigma_{cell} \tag{3}$$

where $(\sigma_o)_{ss}$, $\sigma_{pearlite}$, σ_{colony} and σ_{cell} represent the resistance to dislocation motion resulting from solid solution additions ($(\sigma_o)_{ss}$), pearlitic plate spacing ($\sigma_{pearlite}$), pearlite colony size (σ_{colony}) and dislocation cell size (σ_{cell}). The $(\sigma_o)_{ss}$, $\sigma_{pearlite}$, σ_{colony} terms for hypereutectoid steels are given in Equation (1). The σ_{cell} term is the dominant source of strengthening in Fig. 2 (assuming in a severely drawn wire that the yield strength equals the tensile strength). The data in Fig. 2 suggests that for severely drawn wire the cell size dominates the strength of the wire, and the pearlite spacing and pearlite colony size are secondary contributors. Furthermore, this view agrees with the continuous nature of the data shown in Fig. 4, which compares a pearlitic structure wire with a totally ferritic structure wire. The σ_{cell} data in Fig. 4 is for a single composition hypereutectoid steel. It is informative to examine the strength increment due to drawing for all the steels shown in Fig. 2. The results are shown in Fig. 5, which shows a good correlation between the incremental increase in strength and the drawing strain. There is some scatter in the data; the general trend, however, is that steels with higher carbon content have higher strength increments for a given amount of drawing strain.

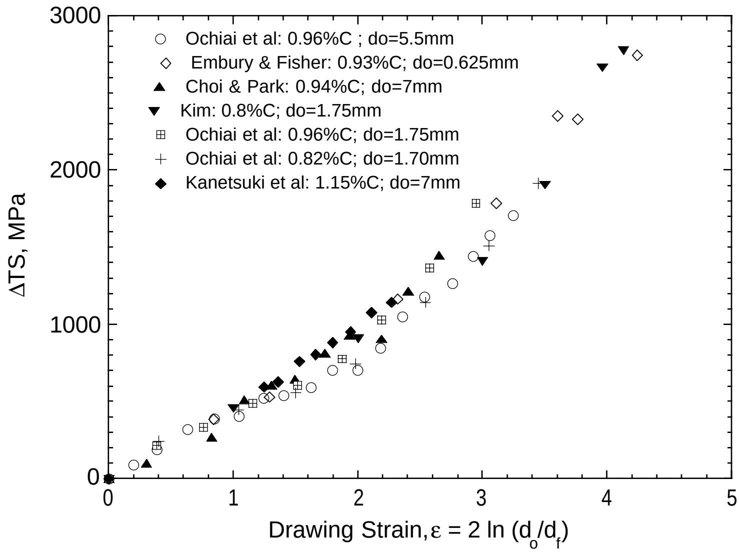

Fig. 5. Strength increment as a function of wire drawing strain for the eutectoid and hypereutectoid steels shown in Fig. 3.

The second observation that can influence the strength levels in Figs. 2, 3, 4 and 5 is the size of the initial cells that form. As noted by Embury and Fisher, who compared dislocation substructures produced in commercially pure iron and Fe-.93C (with both coarse and fine pearlite), the presence of carbide plates produced a smaller initial cell size in the ferrite. In addition, reducing the interlamellar spacing through suitable heat treatment reduced the initial cell size. Thus, by analogy, increasing the carbon content for a given carbide-to-carbide distance in pearlite will reduce the mean free ferrite path and thus the initial cell size. Since the cell thickness scales with wire diameter during drawing [1], smaller cell sizes (and higher strengths) are possible for a given drawing strain. These conclusions are consistent with experimental observations by Ochiai [10, 14] on eutectoid and hypereutectoid steel wires in that both the as-patented strength and the work hardening rate increased with increasing carbon content.

Modeling of Strength Evolution

The model for strength evolution of a pearlitic, eutectoid-composition steel during wire drawing is derived from Equation (3), which assumes that individual strengthening mechanisms do not influence one another and contribute to the overall strength in an additive manner. Combining Equations (1) and (3) results in Equation (4)

$$\sigma_y = (\sigma_o)_{ss} + 145(D)^{-1/2} + 460L^{-1/2} + \sigma_{cell} \qquad (4)$$

In addition, we assume that during wire drawing the evolution (increase) in strength produced by these various mechanisms results from a decrease in the barrier spacing. As suggested by

Embury and Fisher for the interlamellar spacing in pearlite, the evolution of microstructural features controlling the dislocation barrier spacing scales with the initial wire diameter. Thus during the wire drawing process, the microstructures exhibit similitude and

$$d_o/d = D_o/D = L_o/L = \lambda_o/\lambda \tag{5}$$

where d_o is the initial wire diameter, d is the current wire diameter, D_o is the initial carbide spacing, L_o is the initial pearlite colony size and λ_o is the initial cell size developed early in the drawing process. Since the drawing strain (ε) is equal to

$$\varepsilon = 2\ \ln(d_o/d), \tag{6}$$

the evolution of the various dislocation barrier spacings with drawing strain can be obtained from

$$d_o/d = \exp(\varepsilon/2). \tag{7}$$

Using this analysis it is possible to predict the cell size as a function of drawing strain. The results are shown in Fig. 6 assuming a stable cell size of 60 nm develops after a strain of 0.8.

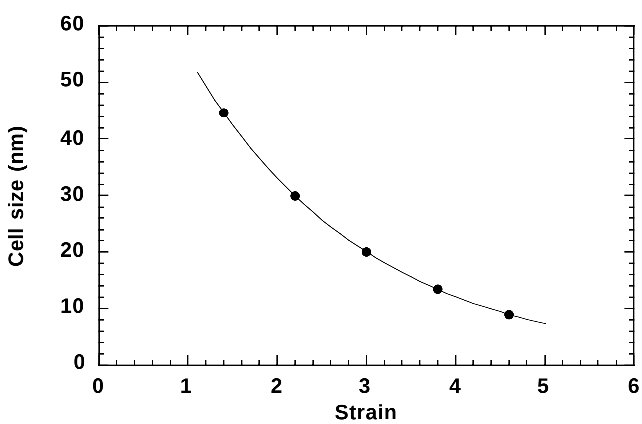

Fig. 6. Influence of drawing strain on cell size assuming similitude and a cell size of 60 nm at ε = 0.8.

The strengthening contribution of the cellular substructure can be derived from the stress necessary to activate a dislocation source. The problem is shown conceptually in Fig. 7, which shows a dislocation bowing out between the cell walls. Activation of this dislocation source requires bowing the dislocation to a semi-circular shape. Sevillano [15] and Languillaume et al. [16] have provide an expression for this stress, namely

$$\sigma_{cell} = (MAGb/2\pi\lambda)\ \ln(\lambda/b) \tag{8}$$

where M is an orientation factor (assumed as 1.84 for the <110> wire texture), A is a constant (equal to 1.2 for a mixed dislocation), G is the shear modulus ($6.4\cdot10^4$ MN/m^2) and b ($2.48\cdot10^{-10}$m) is the Burgers vector.

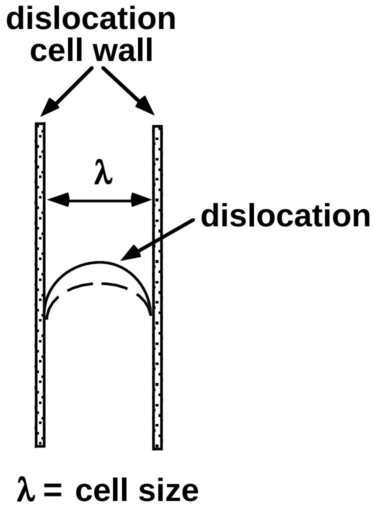

Fig. 7. Activation of a dislocation source within the cell of a severely drawn wire.

Calculations of wire strength as a function of drawing strain were made using the model described above. Values of D_o and L_o (.09 µm and 3.6 µm respectively), which were taken from the work of Taleff et al. [8, 9], are representative of hypereutectoid steels with fine pearlite. The results are shown in Fig. 8 for two different values of $(\sigma_o)_{ss}$ – 20 MPa and 330 MPa. The value of $(\sigma_o)_{ss}$ increases with alloy content and the values used in the calculations represent the range in $(\sigma_o)_{ss}$ that has been observed for low and high alloyed hypereutectoid steels. The figure shows how the strengthening contribution of the four mechanisms evolves with drawing strain. Also shown in the figure are the tensile strength data (plotted as a function of drawing) for the drawn eutectoid and hypereutectoid steels presented in Fig. 2. The model calculations show excellent agreement with the experimental data. The results show that for typical drawing strains (e.g. > 2) the strength of the drawn wire is dominated by the strengthening contributions of the cell structure. In addition, with increasing strain, the hardening rate of the cell strengthening mechanism increases the most. However, despite the importance of the cell structure, the lamellar pearlite plates are still important contributors to strength - e.g. contributing approximately 32% of the strength at a drawing strain of 4. On the other hand, substitutional solute additions contribute very little to the strength of the drawn wire.

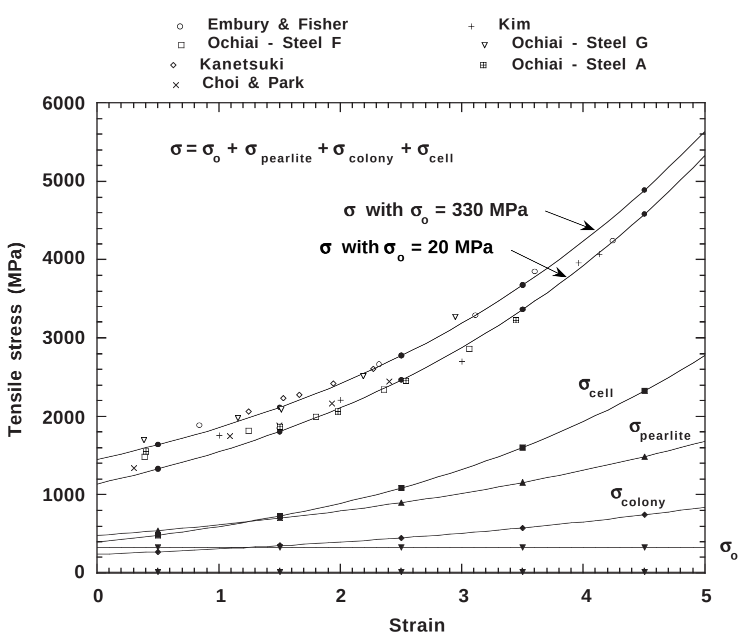

Fig. 8. Wire tensile strength as a function of drawing strain for a eutectoid composition steel with fine pearlite microstructure. The individual strengthening contributions from solid solution additions (σ_o), pearlitic plate spacing ($\sigma_{pearlite}$), pearlite colony size (σ_{colony}) and dislocation cell size (σ_{cell}) are shown in the figure.

Summary and Concluding Remarks

This paper has reviewed the microstructure evolution and the resulting strength of hypereutectoid steels during wire drawing. Mechanisms of strengthening that result from severe wire drawing have been discussed. A model has been developed to describe the evolution of strength during wire drawing. The model predictions for the evolution of tensile strength with drawing strain have been compared with data derived from a number of eutectoid and hyperectectoid. The model shows excellent agreement with experimental data. Important conclusions are as follows.

- Severe plastic deformation during wire drawing of hypereutectoid steels results in considerable alignment of the pearlite plates and the development of a dislocation substructure within the ferrite that resists dynamic recovery. Deformation and fracture of the carbide plates is also observed.
- The yield strength in hypereutectoid steels has been shown to result from additive strengthening contributions from solid solution additions, pearlite spacing, pearlite colony size and dislocation cell size. For severely drawn wire, the strengthening due to dislocation cells can dominate the strength of the wire. However, the lamellar pearlite plates are still important contributors to strength but substitutional solute additions contribute little strength.
- Increasing the carbon content reduces the mean free ferrite path in the as-patented wire and the initial cell size developed during drawing. This results in a higher flow stress in the as-patented wire and a higher work hardening rate.
- Achieving high strength requires a) eliminating the continuous carbide network that can form during cooling from temperatures in the austenite phase field, b) a starting microstructure of fine pearlite, c) alignment of pearlite plates and development of a stable dislocation substructure within the ferrite and d) avoiding fracture.

Acknowledgments

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